ACM MobiHoc 2020

Optimizing Information Freshness using Low-Power Status Updates via Sleep-Wake Scheduling

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Joint work with Yin Sun*, Rahul Singh ‡, and Ness B. Shroff ‡

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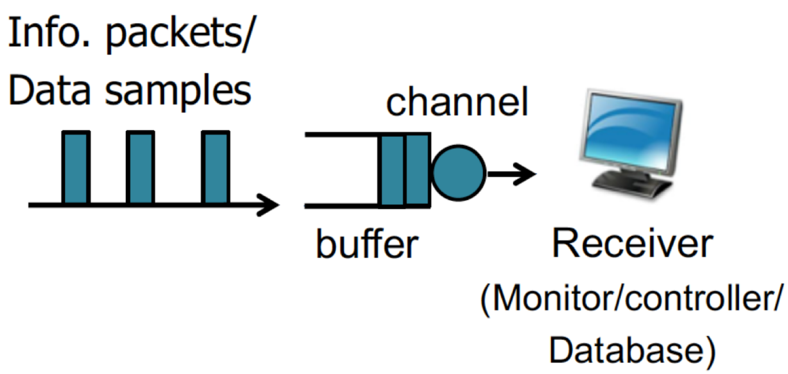
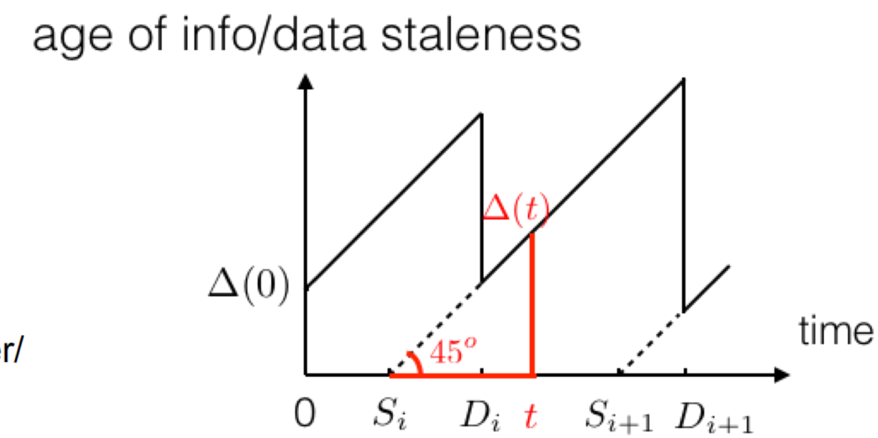
What is the Age of Information?





Definition: at any time t, **the age-of-information (AoI)** $\Delta(t)$ is the "age" of the freshest sample available at the destination before time t

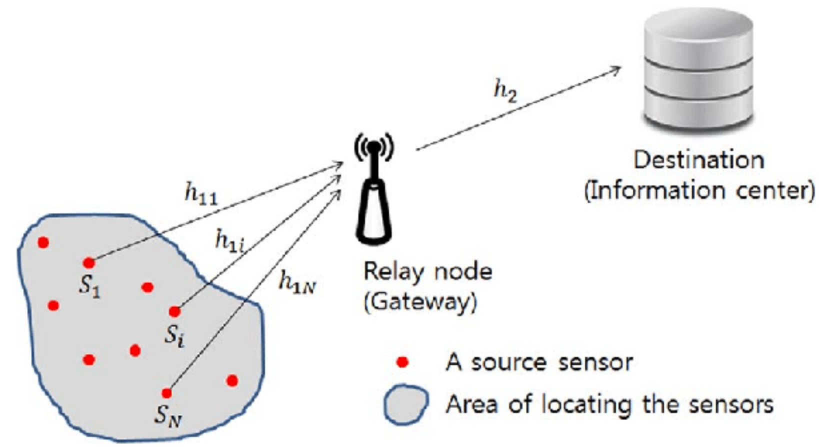
- If sample i is generated at S_i and delivered at D_i

$$\Delta(t) = t - \max\{S_i : D_i \leq t\}$$

- Age grows linearly, and drops upon new sample delivered

Motivation

- **Wireless sensor networks**
  - Sensor nodes in remote or hard-to-reach areas
  - Sharing same channel
  - Required to operate unattended for long durations.
  - Have limited battery capacity



WSN to observe environmental phenomena

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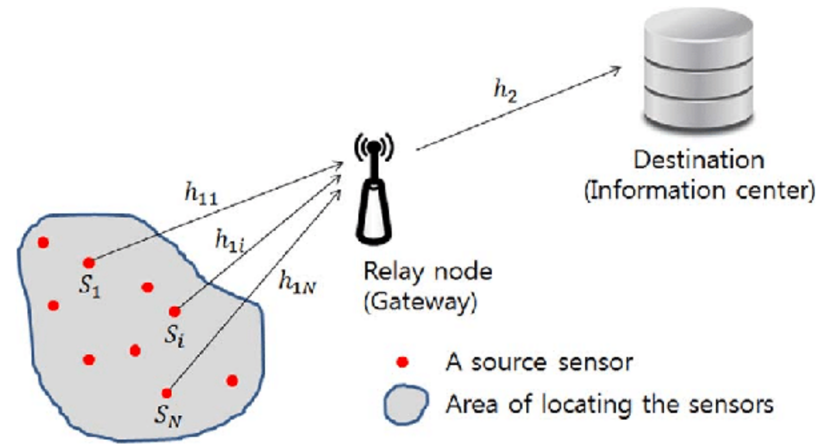

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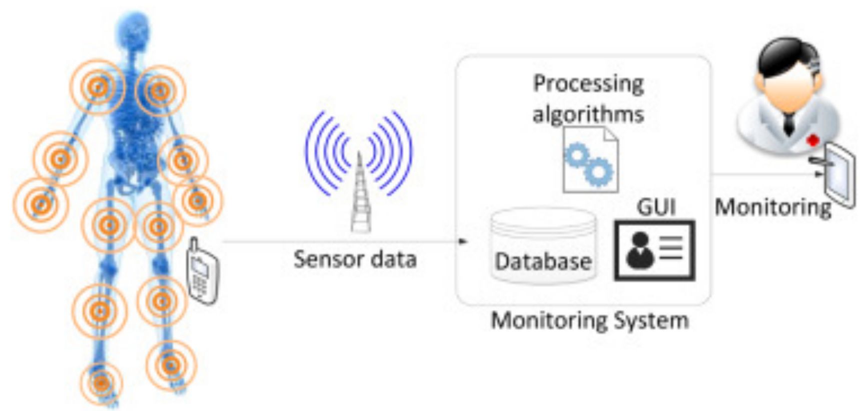

Medical sensor networks

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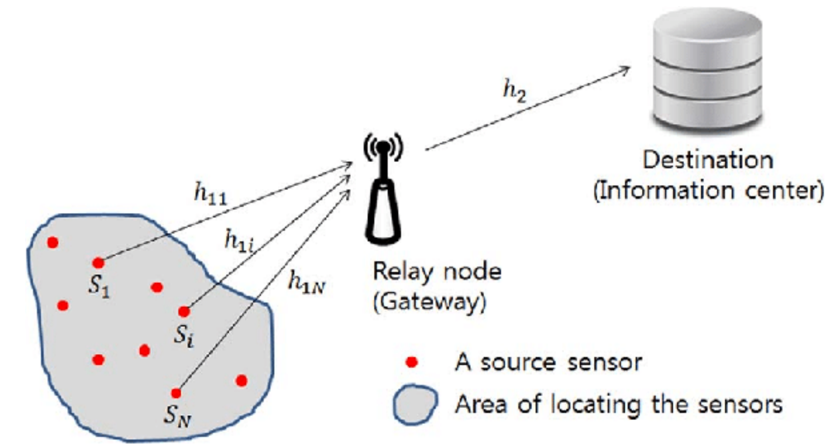
  - Maintain low AoI
  - Long Lifetime



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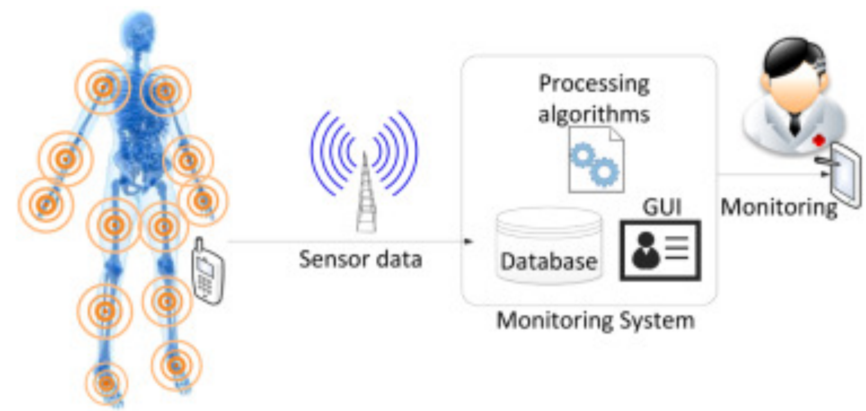

Medical sensor networks

Update less frequently → Energy consumption ↓ → Lifetime ↑ → AoI ↑

Update more frequently → Energy consumption ↑ → Lifetime ↓ → AoI ↓

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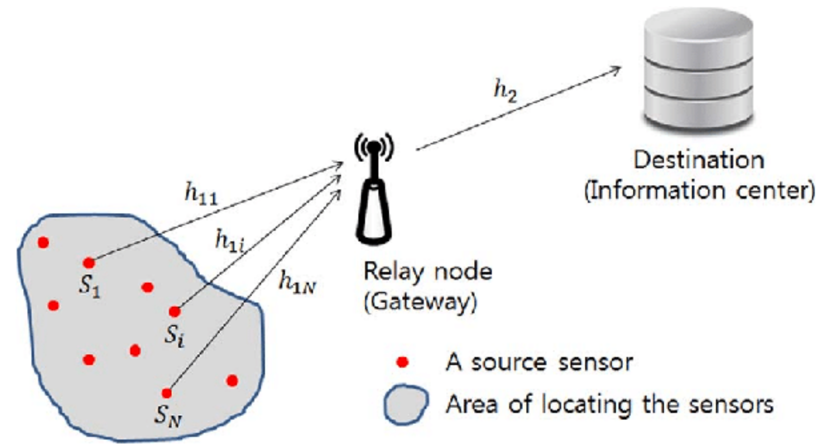

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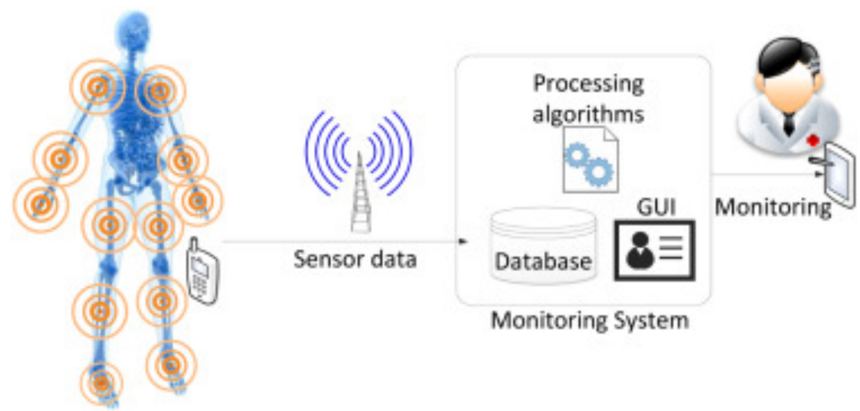
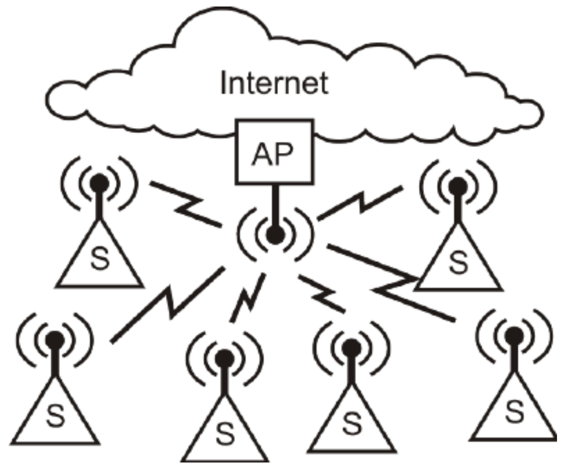


Medical sensor networks

This paper designs an asynchronized scheduling policy that achieves the optimal trade-off between AoI and Lifetime

Our System Model



- Wireless network with M sources
- Sources send update packets to an AP via a shared channel
- Sources utilize carrier sensing to reduce collisions

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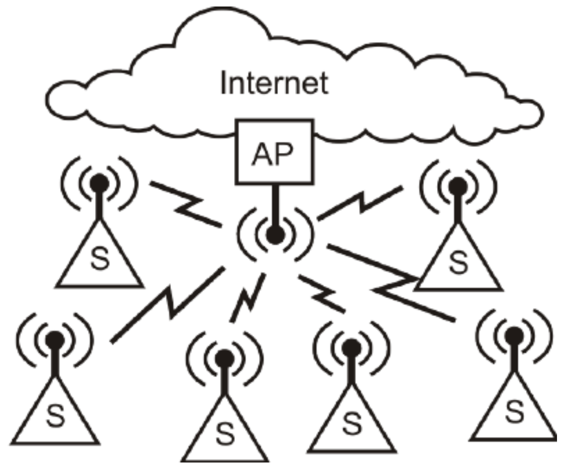
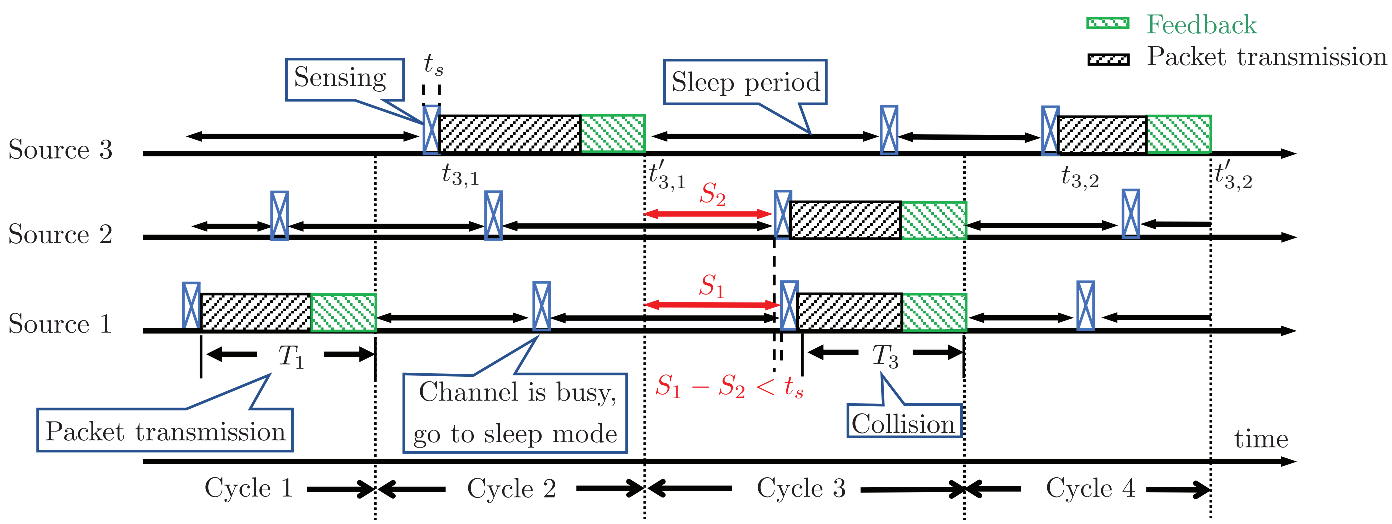


- Wireless network with M sources
- Sources send update packets to an AP via a shared channel
- Sources utilize carrier sensing to reduce collisions
- Each source follows sleep-wake scheme:
  - Generates and transmits a new packet if the channel is sensed idle
  - Sleeps if:
    - Senses the channel to be busy
    - Completes a packet transmission

Our System Model (Cont.)



- Source l sleeping period: Exponentially distributed with mean $\frac{1}{r_l}$
- Transmission times: Arbitrarily distributed with mean $\mathbb{E}[T]$
- Sensing time is t_s
- Collision occurs if two sources start transmitting within a duration of t_s

Scheduler Types

Scheduling policies

Synchronized schedulers

Asynchronized schedulers

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Asynchronized schedulers

- With access probabilities (e.g., for time-slotted systems)

$$\mathbf{a} = \{a_l\}_{l=1}^{M}, \sum_{i=1}^{M} a_i \leq 1$$

- Source l gains channel access after a packet transmission with a probability a_l

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- **Pros:**
  - Good performance
  - No collision
- **Cons:**
  - Require coordination overhead
  - Not implementable in case of:
    - Dense networks
    - Non-constant transmission times
- Ex.:[Talak, Karaman, Modiano 2018]

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Asynchronized schedulers

- Focus of our work
- **Pros:**
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  - Collision occurs due to non-zero sensing time
  - Collision increases AoI and energy consumption

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- Ex: CSMA to minimize AoI
- [Maatouk, Assaad, Ephremides 2019]
- [Wang, Dong 2019]
  - No energy constraint
  - Zero sensing time
  - Some distributions for transmission times

Q: How to Model Energy Cost of Collisions and Target Lifetime?

- Source l equipped with a Battery with initial level of B_l
- Source l has a target lifetime D_l : Minimum time duration before the battery is depleted
- Source l Average energy replenishment rate R_l
- Maximum allowable energy consumption rate for transmissions

$$E_{\mathrm{con},l} = \frac{B_l}{D_l} + R_l$$

- Source l fraction of time transmitting update packets σ_l
- Source l average energy consumption rate in the transmission mode $E_{\mathrm{avg},l}$

$$\sigma_l E_{\mathrm{avg},l} \leq E_{\mathrm{con},l} \quad \Longrightarrow \quad \sigma_l \leq E_{\mathrm{con},l}/E_{\mathrm{avg},l} = b_l$$

b_l : The target energy efficiency of source l

Q: How to Minimize the AoI with Energy (Battery Lifetime) Constraints?

- $1/r_l \uparrow$ ⟶ Energy consumption $\downarrow$ ⟶ Lifetime $\uparrow$ ⟶ AoI $\uparrow$

  $1/r_l \downarrow$ ⟶ Energy consumption $\uparrow$ ⟶ Lifetime $\downarrow$ ⟶ AoI $\downarrow$

- Target: Design r_l's s.t.

$$\bar{\Delta}_{\text{opt}}^{\text{w-peak}} \triangleq \min_{r_l>0} \sum_{l=1}^{M} w_l \mathbb{E}[\Delta_l^{\text{peak}}]$$
$$\textbf{s.t. } \sigma_l \leq b_l, \forall l,$$

Δ_l^{Peak} : Peak age of source l

w_l : Weight of source l

$\Downarrow$

$$\bar{\Delta}_{\text{opt}}^{\text{w-peak}} \triangleq \min_{r_l>0} \sum_{l=1}^{M} \frac{w_l e^{-r_l \frac{t_s}{\mathbb{E}[T]}}}{r_l} e^{\sum_{i=1}^{M} r_i \frac{t_s}{\mathbb{E}[T]}} \left(1 + \sum_{i=1}^{M} r_i\right) + \sum_{l=1}^{M} w_l$$
$$\textbf{s.t. } \frac{[1 - e^{-r_l \frac{t_s}{\mathbb{E}[T]}}] \sum_{i=1}^{M} r_i + r_l e^{-r_l \frac{t_s}{\mathbb{E}[T]}}}{\sum_{i=1}^{M} r_i + 1} \leq b_l, \forall l,$$

Non-convex optimization problem (non-convex constraints)

Q: How to Minimize the AoI with Energy (Battery Lifetime) Constraints? (Cont.)

- Derive a low-complexity solution → Near-optimal when $\frac{t_s}{\mathbb{E}[T]}$ is small
- $\mathbf{r}^\star := (r_1^\star, \ldots, r_M^\star)$

$$r_l^\star = \min\{b_l, \beta^\star \sqrt{w_l}\} x^\star, \forall l,$$

Energy-adequate regime

Energy-scarce regime

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Energy-adequate regime

$$\sum_{i=1}^{M} b_i \geq 1$$

- Sufficient energy to ensure that at least one source is awake at any time

$\beta^\star$: the root of

$$\sum_{i=1}^{M} \min\{b_i, \beta^\star \sqrt{w_i}\} = 1$$

$$x^\star = \frac{-1}{2} + \sqrt{\frac{1}{4} + \frac{\mathbb{E}[T]}{t_s}},$$

Energy-scarce regime

Q: How to Minimize the AoI with Energy (Battery Lifetime) Constraints? (Cont.)

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$$x^\star = \frac{-1}{2} + \sqrt{\frac{1}{4} + \frac{\mathbb{E}[T]}{t_s}},$$

Energy-scarce regime

$$\sum_{i=1}^{M} b_i < 1$$

- Sources have to sleep for some time to meet the sources' energy constraints

$$x^\star = \frac{\min_l c_l}{1 - \sum_{i=1}^{M} b_i}, \quad \beta^\star = \sum_{i=1}^{M} \frac{1}{\sqrt{w_i}}$$

$$c_l = \frac{2b_l \left(1 - \sum_{i=1}^{M} b_i\right)^2}{Q}$$

$$Q = b_l \left(1 - \sum_{i=1}^{M} b_i\right)^2 + \sqrt{b_l^2 \left(1 - \sum_{i=1}^{M} b_i\right)^4 + 4b_l^2 \left(1 - \sum_{i=1}^{M} b_i\right)^2 \left(\sum_{i=1}^{M} b_i - b_l\right) \frac{t_s}{\mathbb{E}[T]}}$$

Main Results

Theorem:

- Our solution is near-optimal when $\frac{t_s}{\mathbb{E}[T]}$ is sufficiently small, i.e.,
  - If $\sum_{i=1}^{M} b_i \geq 1$, $\left| \bar{\Delta}^{\text{w-peak}}(\mathbf{r}^\star) - \bar{\Delta}^{\text{w-peak}}_{\text{opt}} \right| \leq 2\sqrt{\frac{t_s}{\mathbb{E}[T]}} C_1 + o\left(\sqrt{\frac{t_s}{\mathbb{E}[T]}}\right)$
  - If $\sum_{i=1}^{M} b_i < 1$, $\left| \bar{\Delta}^{\text{w-peak}}(\mathbf{r}^\star) - \bar{\Delta}^{\text{w-peak}}_{\text{opt}} \right| \leq \frac{t_s}{\mathbb{E}[T]} C_2 + o\left(\frac{t_s}{\mathbb{E}[T]}\right)$

  C_1, C_2 : Constants

- Our solution is asymptotically optimal as $\frac{t_s}{\mathbb{E}[T]} \to 0$, i.e.,

$$\lim_{\frac{t_s}{\mathbb{E}[T]} \to 0} \left| \bar{\Delta}^{\text{w-peak}}(\mathbf{r}^\star) - \bar{\Delta}^{\text{w-peak}}_{\text{opt}} \right| = 0$$

Main Results

Corollary: the performance of our proposed algorithm is asymptotically no worse than any synchronized scheduler, i.e., we have

$$\lim_{\frac{t_s}{\mathbb{E}[T]}\to 0} \bar{\Delta}_{\text{opt}}^{\text{w-peak}} = \bar{\Delta}_{\text{opt-s}}^{\text{w-peak}}.$$

$\bar{\Delta}_{\text{opt-s}}^{\text{w-peak}}$: Optimal weighted average peak age for synchronized scheduler

Proof Steps

- **Step1:**
  - Check the feasibility of the solution: (Satisfying the energy constraint)
  - Construct an upper bound: Substitute our solution into the obj. function

Proof Steps

- **Step1:**
  - Check the feasibility of the solution: (Satisfying the energy constraint)
  - Construct an upper bound: Substitute our solution into the obj. function
- **Step 2:**
  - Construct a lower bound by relaxing the constraints

$$\min_{r_l>0} \sum_{l=1}^{M} \frac{w_l e^{-r_l \frac{t_s}{\mathbb{E}[T]}}}{r_l} e^{\sum_{i=1}^{M} r_i \frac{t_s}{\mathbb{E}[T]}} \left(1+\sum_{i=1}^{M} r_i\right) + \sum_{l=1}^{M} w_l$$

$$\textbf{s.t.} \ \frac{[1-e^{-r_l \frac{t_s}{\mathbb{E}[T]}}]\sum_{i=1}^{M} r_i + r_l e^{-r_l \frac{t_s}{\mathbb{E}[T]}}}{\sum_{i=1}^{M} r_i + 1} \leq b_l, \forall l,$$

$$\Downarrow$$

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$$\textbf{s.t.} \ r_l \leq b_l \left(\sum_{i=1}^{M} r_i + 1\right), \forall l,$$

Proof Steps (Cont.)

- **Step 3:**
  - Analysis the gap between the upper and lower bounds
  - This characterizes the sub-optimality gap of our solution

Easy Implementation

- Uniform solution formula for both energy regimes

$$r_l^\star = \min\{b_l, \beta^\star \sqrt{w_l}\} x^\star, \forall l,$$

- Each source just needs $\beta^\star \& x^\star$ to compute its sleeping period parameter
- $\beta^\star \& x^\star$ are functions of $\{(w_i, b_i)_{i=1}^M, t_s/\mathbb{E}[T]\}$

Algorithm 1: Implementation of sleep-wake scheduler.

The AP gathers the parameters $\{(w_i, b_i)_{i=1}^M, t_s/\mathbb{E}[T]\}$;
if $\sum_{i=1}^M b_i \geq 1$ **then**
  The AP derives $x^\star$, $\beta^\star$ according to (19) and (20); → Energy-adequate regime formulas
else
  The AP derives $x^\star$, $\beta^\star$ according to (25) - (27); → Energy-scarce regime formulas
end
The AP broadcasts $x^\star$, $\beta^\star$ to all the M sources;
Upon hearing $x^\star$, $\beta^\star$, source l compute $r_l^\star$ from (18);

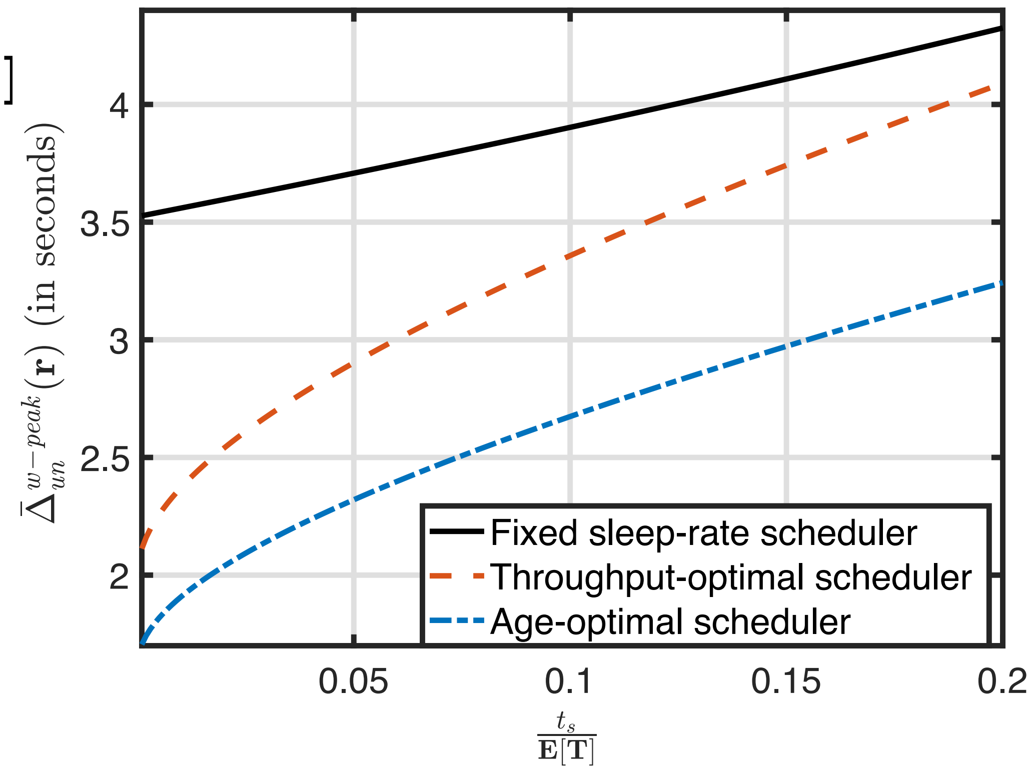
Simulation Results

Fixed-rate: Fixed rates for all sources

Throughput-optimal: Throughput sleep-wake optimal scheduler in [1]

Simulation settings:

- $\mathbb{E}[T] = 5$ ms
- w_l's are uniformly in [0, 10]
- $M = 10$ sources
- b_l's are uniformly in [0, 1]



Observations:

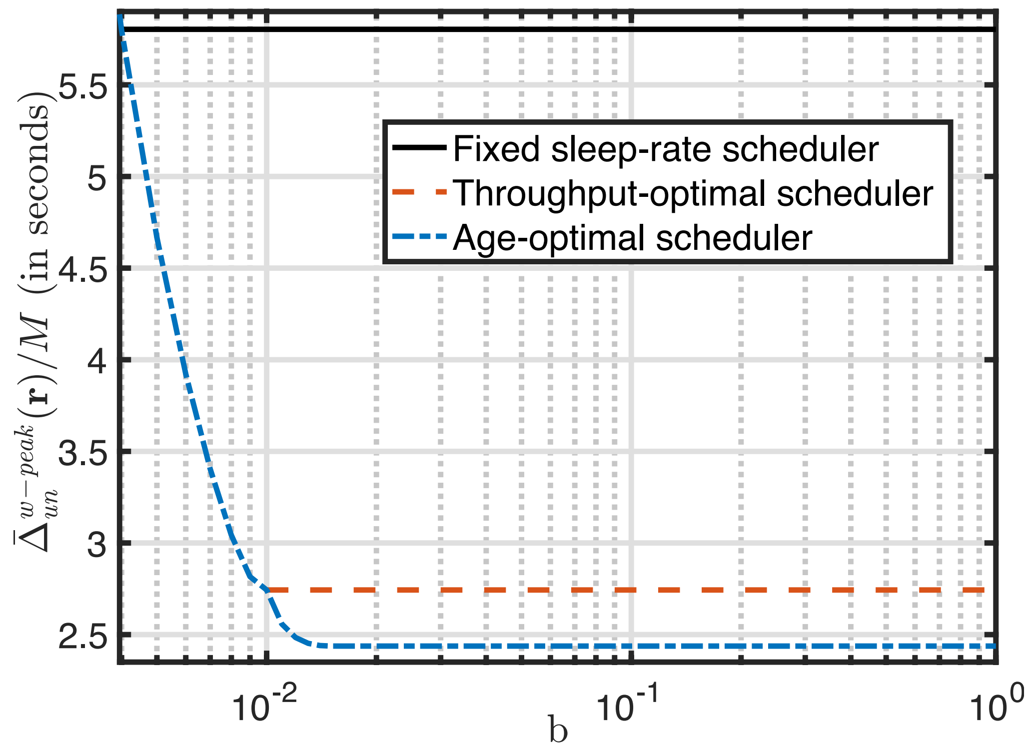
1. t_s increases → Packet collision increases → AoI increases
2. Age-optimal scheduler outperforms other policies (Throughput optimal scheduler is not necessarily age-optimal)

[1] S. Chen, T. Bansal, Y. Sun, P. Sinha, and N. B. Shroff. 2013. Life-Add: Lifetime Adjustable design for WiFi networks with heterogeneous energy supplies. In Proc. WiOpt. 508–515.

Simulation Results (Cont.)

Simulation settings:

- $\mathbb{E}[T] = 5$ ms
- w_l 's are uniformly in [0, 10]
- $M = 100$ sources
- $b_l = b\ \forall l$



Note: Throughput-optimal scheduler is not feasible for $b \leq 0.01$

Observations: $r_l^\star = \min\{b_l, \beta^\star\sqrt{w_l}\}x^\star, \forall l,$

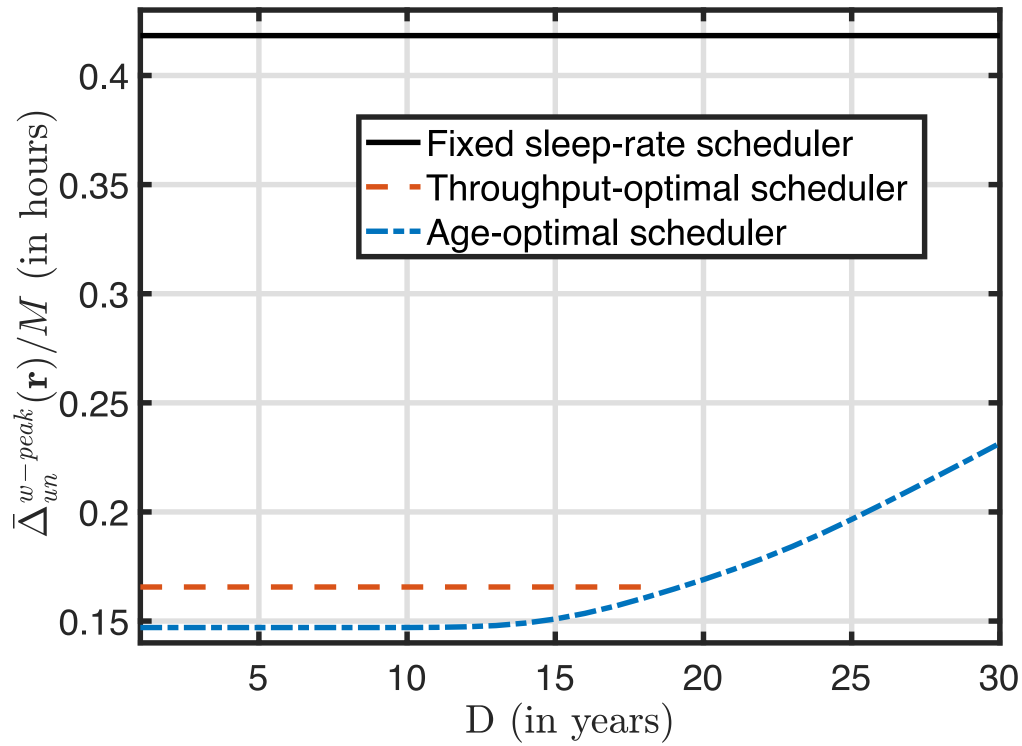
1. There is a value for b after which $\mathbf{r}^\star$ is a function solely of w_l 's & $\beta^\star$
2. Age-optimal scheduler outperforms other policies (Throughput optimal scheduler is not necessarily age-optimal)

Simulation Results (Cont.)

Simulation settings:

- $\mathbb{E}[T] = 5$ ms
- w_l's are uniformly in [0, 2]
- $M = 10^5$ sources (dense netw)
- $B_l = 8$ mAh, $V_{\text{out}} = 5$ Volt, $E_{\text{cons},l} = 24.75$ mW, $\forall l$
- $D_l = D, \ \forall l$ (Target lifetime)

Note: Throughput-optimal scheduler is not feasible for $D > 18$ years



Observations:

1. D increases → Sleeping periods increases → AoI increases
2. Age-optimal scheduler can be active for 25 years with a decent average peak age of 0.2 hour, i.e., 12 minutes.
3. Age-optimal scheduler outperforms other policies

Summary

- Target: Efficient sleep-wake mechanism to attain optimal trade-off between minimizing AoI and energy consumption
- Optimization problem is non-convex
- Providing a near-optimal solution when $\frac{t_s}{\mathbb{E}[T]}$ is a sufficiently small
- Providing an easy implementation of our solution
- Our solution is asymptotically no worse than any synchronized scheduler

Q&A

Thanks